Estimation of Mexico's Informal Economy Using DMSP Nighttime Lights Data

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Abstract— **In many countries of the world governments are unable to accurately track the true magnitude of economic activity due to the large number of transactions upon which taxes are not paid. It is particularly easy to avoid paying taxes on cash transactions and on remittances transferred from outside of the country. In some cases the so called "informal economy" is believed to be a substantial fraction of a nation's total gross domestic product (GDP). Using DMSP satellite observed nighttime lights we developed a calibration for estimating reported GDP for the 48 contiguous states of the USA, where the informal economy is rated as relatively low. We applied this calibration to estimate the GDP for the states of Mexico and compared these values to officially reported GDP and Gross National Income (GNI) values. We found that most states in Mexico have a surplus in lighting relative to their officially reported GDP. We attribute this surplus in lighting to the informal economy and have made estimates of the magnitude of this unreported component to the true GDP. The results are encouraging and suggest that this technique could be used in other countries where accurate GDP reporting is problematic.**

I. INTRODUCTION

Measuring and understanding spatial distribution of economic activity is a subject of considerable interest to social scientists. Globalization of the economy in the 1990s resulted in the 'informalization' of the workforce in many industries and countries [1]. Industrialization associated with globalization results in capital intensification, and, workers who lose their jobs resort to informal work. Decentralization of production increases the number of informal (i.e. unregistered economic entities. In an attempt to cut the costs of production many firms subcontract their services to these unregistered entities in countries that have lower labor costs because of these informal arrangements [2]. Households often supplement their incomes from the formal economy by working in the informal economy [3]. The decline in formal employment opportunities for the increasing population of urban areas is another major cause for the rise in informal employment [4]. The increased participation in the informal economy is also associated with neoliberal policies such as the North American Free Trade Agreement (NAFTA).

Mexico was selected as the country of study in this paper because in the past quarter century Latin American countries have adopted these neoliberal doctrines (General Agreement on Tariffs and Trade, NAFTA, and World Trade Organization membership) almost universally, and this has had profound repercussions on the livelihoods of those who live and work in cities [5]. The neoliberal policies of privatization, deregulation and trade liberalization has resulted in the creation of more temporary, low wage and unprotected (i.e., informal) employment [6, 7, 8]. Thus, in the past two decades men and women in cities throughout Latin America have increasingly taken up informal work as a livelihood strategy [8, 9].

Informed activists and researchers have worked with the International Labor Organization (ILO) to clarify the concept and definition of the 'informal sector' of the economy [10]. The research presented in this paper takes a very simple approach to this complex idea. We simply estimate all economic activity using nighttime satellite imagery and ostensibly accurate GDP figures for the United States (U.S.) and apply them to Mexico. The value of the informal economy plus remittances for Mexico is simply the difference between the nighttime-satellite-image-based estimates and the official 'formal' measures of GNI provided by the National Institute of Statistics, Geography and Computer Science (Instituto Nacional de Estadistica, Geografia e Informatica, INEGI) [11].

The contribution of the informal economy towards the Gross Domestic Product (GDP) of a country, especially for developing countries can be considerable. Compiling statistics on the size, composition and contribution of the informal economy is an extremely complicated exercise. The

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main difficulty is that very few countries have undertaken regular surveys of the informal sector and only two or three countries have collected data that provide measures of informal employment outside informal enterprises. Also, there are a number of problems that hinder the international comparability of data as countries apply different criteria for non-registration, enterprise size and/or workplace location [3].

Remittances contribute to the Gross National Income (GNI) of a country, where GNI is the sum of Gross Domestic product (GDP) plus net receipts of compensation of employees and property income from abroad. Remittances are the funds that the international migrants send back to their countries of origin. The quality and coverage of data on remittances is fraught with problems. In several countries many types of formal remittance flows go unrecorded, due to weaknesses in data collection (related to both definitions and coverage) and flows through informal channels (such as unregulated money transfers or family and friends who carry cash). Remittances are frequently misclassified as export revenue, tourism receipts, nonresident deposits, or even foreign direct investment (FDI) [12].

Reliable measurements of the economic transactions of a nation expressed in terms of GNI and GDP are difficult to obtain because of the lack of well developed national income accounting methods and the large size of the “informal” sector, especially in developing economies [13, 14]. Official estimates of the GNI and GDP of countries can vary dramatically depending on the sources of data and the different accounting methods.

Remote sensing data provides an interesting alternative for measuring the values of these economic activities as such data provide a synoptic view of the terrestrial environment and are applied extensively to map the spatial distribution of population and to examine the impact of human presence on the environment [15]. For example, the Defense Meteorological Satellite Programs Operation Linescan System (DMSP OLS) detects city lights, forest fires, gas flare burn-off, and lantern fishing, all produced by human activities [16]. Therefore, the DMSP OLS can serve as a proxy measure of population and correlates of population such as economic activity and energy consumption [17]. Nighttime imagery has been used for myriad applications including estimation of urban populations [18, 19, 20, 21], estimation of intra-urban population density [22, 23], energy utilization or electric power consumption [18, 19, 21, 24], delineating urban land cover [21, 25], measuring anthropogenic impervious surface area [26], estimating GDP at the national and sub-national level [14, 21, 24, 27, 28], mapping marketed and non-marketed economic activity [29], estimation and mapping of CO_2 emissions [27], mapping ‘exurban’ areas [30], mapping nocturnal squid fishing [31], and mapping fire and fire-prone areas [32].

Due to the problems associated with estimating the magnitude and spatial distribution of economic activity, we explore an alternative method. Building upon previous efforts, this paper explores the potential for estimating the values of the economic activities of GDP, informal economy and remittances for Mexico using known relationships between the spatial patterns of nighttime satellite imagery and economic activity in the U.S. Using the arguably more reliable measures of GDP for the states of the U.S. and assuming the contribution of the informal economy towards GDP in the U.S. to be approximately 10 percent [33, 34, 35, 36], we developed a calibration for estimating the reported GDP of the 48 contiguous states of the U.S. The calibration was then used to estimate the GDP of the states of Mexico and was compared to the official GDP and GNI estimates, remittance, and informal economy estimates of INEGI.

II. METHODS

Data Used

A. Radiance-calibrated nighttime satellite imagery data

Sections from Mexico and the United States of a global radiance-calibrated ‘city lights of the world’ data product were used as a proxy measure of economic activity. This data were derived from hundreds of orbits of the DMSP OLS [37]. Different gain settings of the F12 and F15 satellites were used to make the radiance calibrated image of 2000-2001. The different gain settings were normalized to the 55 decibel (dB) gain setting of F15. The radiance value per digital number (DN) detected in the data acquired at the gain of 55 dB was $1.35 * 10^{-10}$ watts/cm^2/sr and the saturation radiance was $8.54 * 10^{-10}$ watts/cm^2/sr. The range of the radiance value of the image is 0 watts/cm^2/sr and $6.73 * 10^{-7}$ watts/cm^2/sr. The data are referenced by latitude/longitude World Geodetic System (WGS 1984) coordinates. Projection of the radiance calibrated nighttime image was changed from the geographic projection to that of the Mollweide equal area projection for an accurate representation of all areas of the earth, from the equator to the poles. The data are in one kilometer square pixels.

B. Landscan Population Dataset

The Landscan population dataset of the year 2000 was used in this study. It comprises a world population database compiled on 30 arc-second grids. It was developed as part of the Oak Ridge National Laboratory (ORNL) Global Population Project for estimating ambient populations at risk. This dataset has been developed by apportioning census counts (at sub-national) level to each grid cell based on likelihood coefficients based on proximity to roads, slope, land cover, nighttime lights, and other information. The data are in Geographic projection referenced by latitude/longitude (WGS 1984) coordinates [38].

C. Official estimates of the GDP and GNI data for the U.S. and Mexico

Gross Domestic Product (GDP) is the value of all final goods and services produced within the borders of a country’s economy in a year. Gross National Income (GNI)

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is the sum of GDP plus net receipts of compensation of employees and property income from abroad. The GDP for all the states of the U.S. for the year 2000 were obtained from the U.S. Bureau of Economic Analysis [39]. The total GDP data was also obtained from the World Development Report, 2002 [40]. The GNI data was obtained from the World Development Report, 2002 [40] and was also calculated by multiplying the GNI per capita and Mid-2000 population data acquired from the 2000 World Population Data Sheet [41].

For Mexico, the GDP data of all the states for the year 2000 was obtained from INEGI. These are the data on *Producto interno bruto por entidad federative, Total de la actividad económica* (Gross internal product by Federal Organization, Total of the economic activity) that were gathered from INEGI's website [42]. The data available were in Thousands of Pesos, and were converted into U.S. dollars on the basis of the official exchange rate as well as the purchasing power conversion factor. Several sources of GNI data were obtained, including the World Development Report, 2002 [40] and the World Population Data Sheet by multiplying the GNI per capita with the mid-2000 population [41]. The discrepancies between these data sources are clearly visible in Tables 1 and 2 below. Nevertheless, the GDP data derived from the U.S. Bureau of Economic Analysis are assumed to be the most reliable official estimates of GDP as the U.S. has the financial and technological resources to conduct elaborate and extensive economic surveys, which the developing countries often lack. The analysis is based on these GDP data (in bold). Also, since the Purchasing Power Parity (PPP) values are the standard used for international comparisons, the GNI data and the GDP data of Mexico derived from INEGI were converted into PPP U.S. dollars and have been used for comparing the results (in bold).

D. *Official estimates of the informal economy and remittances of Mexico*

Data on the contribution of the informal economy in total GDP for Mexico for the year 2000 were obtained from INEGI [43]. A state-wise breakdown of the data was not available and only the total contribution of the informal economy towards GDP was acquired. According to INEGI the contribution of the informal economy towards GDP of Mexico for the year 2000 was 99 billion PPP US dollars, approximately 12.3 percent of the total GDP.

TABLE I. COMPARISON OF GNI AND GDP DATA OF THE U.S. FROM DIFFERENT SOURCES

Country	Estimate	Year	Source	Method	Value
U.S.	GNI	2000	World Development Report, 2002	Atlas method- using 3 year average exchange rate	$ 9,646 billion
U.S.	GNI	2000	Population Reference Bureau	In US Dollars	$ 8,059 billion
U.S.	GDP	2000	World Development Report, 2002	Average official exchange rate of that year	$ 9,883 billion
U.S.	**GDP**	**2000**	**U.S. Bureau of Economic Analysis**	**Current US$**	**$ 9,749 billion**

TABLE II. COMPARISON OF GNI AND GDP DATA OF MEXICO FROM DIFFERENT SOURCES

Country	Estimate	Year	Source	Method	Value
Mexico	GNI	2000	INEGI	In Pesos	5,491 billion
Mexico	GNI	2000	INEGI	In terms of exchange rate U.S. Dollars	$ 574 billion *
Mexico	GNI	2000	**INEGI**	**PPP U.S. Dollars**	**$ 886 billion ***
Mexico	GNI	2000	World Dev. Report 2002	Atlas Method - using three year average exchange rate	$ 498 billion
Mexico	GNI	2000	World Dev. Report 2002	PPP U.S. Dollars	$ 864 billion ▲
Mexico	GNI	2000	Population Reference Bureau	In U.S. Dollars	$ 382 billion
Mexico	GDP	2000	INEGI	In Pesos	4,984 billion
Mexico	GDP	2000	INEGI	In terms of exchange rate U.S. Dollars	$ 521 billion ♦
Mexico	**GDP**	**2000**	**INEGI**	**PPP U.S. Dollars**	**$ 804 billion ♦**
Mexico	GDP	2000	World Dev. Report 2002	Average official exchange rate of that year	$ 575 billion
Mexico	GDP	2000	World Dev. Report 2002	PPP U.S. Dollars	$ 896 billion ∞

a. *Calculated from row 1 in Table 2

b. ▲Calculated from row 4 in Table 2

c. ♦Calculated from row 7 in Table 2

d. ∞ Calculated from row 10 in Table 2

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The data on the total flow of remittances into Mexico for the year 2000 was obtained from Banco de Mexico [44]. The contribution of remittances towards GDP for Mexico for the year 2000 was 0.8 percent, a total value of 6.6 billion dollars. Although the percentage might seem small in comparison to the large economy of Mexico, Mexico is the world's largest remittance receiving country [45].

Data Analysis

We develop a calibration model to estimate the informal economy and remittances of Mexico based on the law of allometric growth. The law of allometric growth, originally developed by biologists, states that the relative growth of an organ is a constant fraction of the state of relative growth of the total organism [46]. Taking 'y' to be the organ and 'x' to be the organism, the law of allometric growth can be expressed as $y = ax^b$. Taking the logarithm of both sides the linear equation is thus: log y = b* log x + log a. Based on this law of allometric growth, Tobler (1969) [47] established that human population could be estimated with a high degree of accuracy by measuring the area of human settlements as observed from satellite photography.

A. Basic assumptions and rationale of the Calibration Model

- Economic activity creates the same spatial patterns of nighttime lights in Mexico and the United States (i.e., there are no cultural, socio-economic, or demographic 'correction factors').
- Spatial patterns of GDP per capita and spatial patterns of distribution of income (i.e., Gini coefficients) are uniform (but not necessarily equivalent) in both the United States and Mexico.
- Estimates of urban populations are used as a proxy measure of the value of economic activity because spatially disaggregate GDP data are either unavailable or simply do not exist.

Consequently, we can develop a relatively simple multiple regression calibration model that predicts the GDP of the 48 contiguous states of the United States. These regression parameters, derived from reliable measures of GDP in the United States are then applied to the spatial patterns of nighttime lights in Mexico to estimate the GDP of the states of Mexico.

B. Demarcating the lit populated areas on the radiance calibrated image of the U.S

First, the radiance-calibrated DMSP-OLS image of the U.S. was used to delineate the lit populated areas. Google Earth was used in tandem with polygons derived from different levels of thresholds on the nighttime image with the aim of including sparsely populated urban areas. The threshold of $20 * 1.35 * 10^{-10}$ watts/cm^2/sr was empirically determined as the appropriate threshold value. The same threshold was used to delineate the lit urban areas of Mexico.

C. The Ln (Area) versus Ln (Population) relationship for the U.S.

Urban populations of all lit areas in the threshold of $20 * 1.35 * 10^{-10}$ watts/cm^2/sr and above in the nighttime image of the U.S. were estimated based on the law of allometric growth [46, 47]. Areas of the lit urban settlements of all the states of the U.S., which were demarcated using the threshold, were estimated. The 'thresholded' nighttime image was then used to mask the Landscan population grid in order to extract the populations of the U.S. states in the areas within and above the threshold value. This created a table of urban settlements of the U.S. states, which included both area and population attributes. The calibration log-log regression model to estimate urban population of the 48 contiguous U.S. states was developed using these area and population attributes. Equation (1) shows the log-log linear model between the areal extent of urban areas and population based on the law of allometric growth. Equation (2) shows the model with α and β parameters for estimating the urban population of the states of the U.S. The estimated urban population of the 48 U.S. states is derived from the exponential of the logarithmic equation [14]. The model is shown in Fig. 1.

$$y = \alpha x^{\beta}$$

population = α (area)$^{\beta}$, which can be written in the log-log form as:

$$\log(\text{population}) = \alpha + \beta * \log(\text{area})$$

$$\text{Estimated urban population} = \text{Exp}(\alpha + \beta * \log(\text{area})) \quad (1)$$

$$\text{Ln (EstUrbPop)} = 5.1090583 + 1.0704396 * \text{Ln (Area)}$$

$$\text{Estimated urban population of the states of the U.S.} = \text{Exponential}(5.1090583 + 1.0704396 * \text{Ln (Area)}) \quad (2)$$

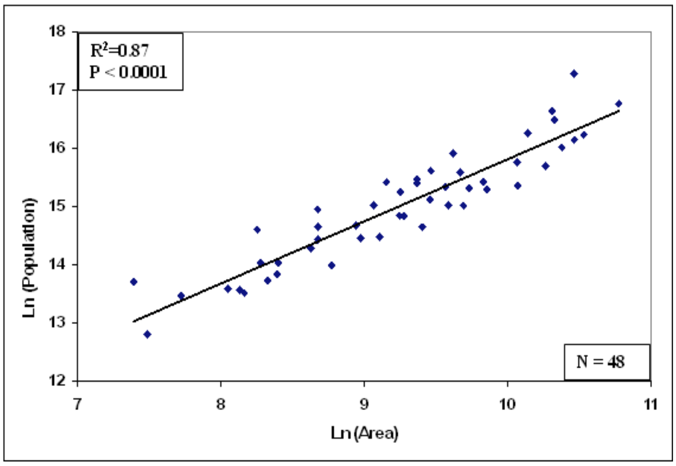

Figure 1. The log-log linear regression model of the area and population of the urban areas of the states of the U.S.

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D. The Ln (Estimated urban population) versus Ln (Actual GDP) relationship for the U.S.

In the next step, a multiple regression calibration model was developed for estimating GDP of the 48 states of the U.S. The multiple regression model was developed on the basis of the assumption that estimates of urban populations could serve as proximate measures of economic activity because spatially disaggregate GDP data are often not available. The estimated urban population of the 48 states of the U.S. and the 'sum of lights'(aggregation of the light intensity values of all the lit areas) are the predictors in the model for estimating the GDP of the 48 U.S. states. The 'sum of lights' (even those below the threshold level) were estimated in order to take into consideration the economic activities detected from lights even below the selected threshold level. The regression equation was weighed by the official GDP values so that the predictor variables, estimated urban population and 'sum of lights' took into account the variation in income among the 48 U.S. states. The estimated GDP values of the 48 U.S. states were derived from the exponential of the logarithmic equation. We predicted the official GDP of each state (inflated by 10% to correct for informal economy in the U.S.), using the estimate of the urban populations within that state and the 'sum of lights' within that state. The multiple regression calibration model developed for estimating the GDP of the 48 states is shown in (3) and α and β parameters in the multiple regression equation for estimating GDP of the 48 states is shown in equation (4).

$$\text{Ln (Actual GDP)} = \alpha + \beta_1 * \text{Ln (Estimated Urban Pop)} + \beta_2 * \text{(Sum of Lights)}$$

$$\text{Estimated GDP} = \text{Exponential } (\alpha + \beta_1 * \text{Ln (Estimated Urban Pop)} + \beta 2 * \text{(Sum of Lights)}) \quad (3)$$

$$\text{Ln (Actual GDP)} = 16.107174 + 0.6202327 * \text{Ln (EstUrbPop)} + 0.00000020796 * \text{Sumoflights}$$

$$\text{Estimated GDP of the states of the U.S.} = \text{Exp } (16.107174 + 0.6202327 * \text{Ln(EstUrbPop)} + .00000020796 * \text{(Sumoflights)}) \quad (4)$$

E. The official estimates of the GDP versus the estimated GDP of the states of the U.S.

A 1:1 plot of the actual and estimated GDP values of the U.S. is shown in Fig. 2. The correlation coefficient (R) of the actual versus estimated GDP of the U.S. is 0.81 which indicates a strong association between the two variables. The 1:1 plot shows that the estimated GDP values are close to the actual GDP values for most of the states except for Texas, New York and California, which are the outliers. GDP was overestimated for Texas and underestimated for New York and California.

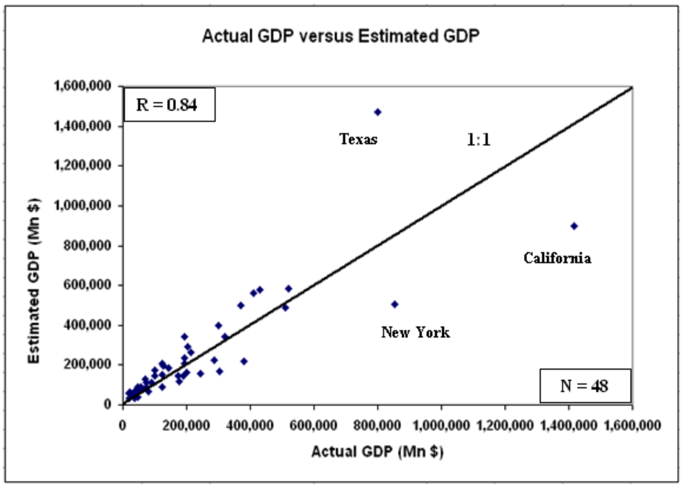

Figure 2. 1:1 plot of the Actual versus Estimated GDP for the U.S. states

F. Demarcating the lit populated areas on the radiance calibrated image of Mexico

We used the same threshold of 20 * 1.35 * 10^{-10} watts/cm^2/sr to delineate the lit populated areas of Mexico in order to apply the parameters we have estimated for the U.S. and to conform to our assumption that economic activity creates the same spatial patterns of light in the U.S. and Mexico.

G. The Ln (Area) versus Ln (population) relationship for Mexico

The areas of the demarcated urban settlements of Mexico were estimated from the nighttime image. After demarcating the urban areas, the slope parameter and the intercept of the urban areas of the U.S. were used to obtain the U.S. equivalent population for the urban areas of the Mexican states (5).

$$\text{Ln (EstUrbPop)} = 5.1090583 + 1.0704396 * \text{Ln (Area)}$$

$$\text{Estimated urban population of the states of Mexico} = \text{Exponential } (5.1090583 + 1.0704396 * \text{Ln (Area)}) \quad (5)$$

H. The Ln (Estimated urban population) versus Ln (Actual GDP) relationship for Mexico

The 'sum of lights' of all the states of Mexico were also measured. The calibration multiple regression model which was developed for the U.S. was used to estimate the GDP of the states of Mexico (6).

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Ln (Actual GDP) = 16.107174 + 0.6202327 * Ln (EstUrbPop) + .00000020796 * Sumoflights
Estimated GDP of the states of Mexico = Exponential (16.107174 + 0.6202327 * Ln (EstUrbPop) + 0.00000020796 * (Sumoflights)) (6)

I. The official estimates of GDP versus the estimated GDP of the states of Mexico

A 1: 1 plot (Fig. 3) of the estimated GDP for each Mexican State (excluding *Distrito Federal, i.e,* Federal District or Mexico City) against the official estimates of GDP of Mexico shows that GDP was overestimated for 27 of the Mexican states and underestimated for one state. The correlation coefficient (R) of the actual versus estimated GDP of the Mexican states (excluding Distrito Federal) is 0.87 which indicates a strong association between the two variables.

Mexico City (i.e., the Federal District) is a primate city and the most important economic hub in the Mexican Republic, producing 21.8 percent of the country's GDP [48]. The city's GDP per capita is the highest of any city in Latin America [49]. Because of these characteristics, it has an outlier effect that distorts our regression parameters and weakens the otherwise strong correlation between the actual and estimated GDP of the Mexican states. Therefore, we excluded Mexico City in the 1: 1 plot of the actual versus estimated GDP of the Mexican states.

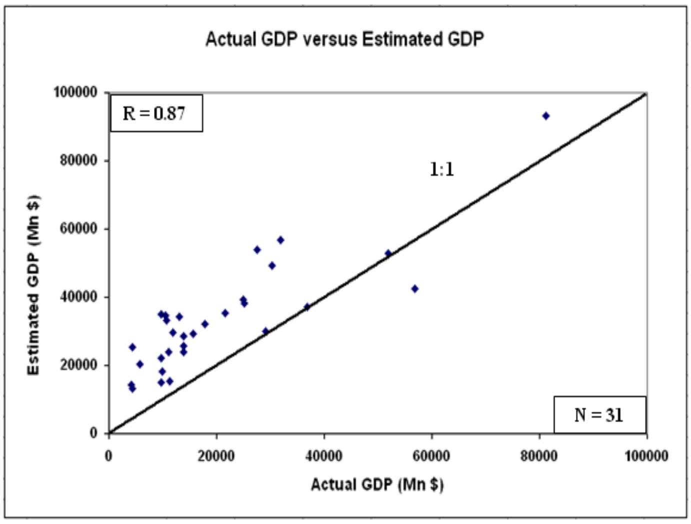

Figure 3. 1:1 plot of the Actual versus Estimated GDP of the Mexican states

J. Estimating the magnitude and spatial distribution of the informal economy and remittances of Mexico and comparing it with the published values

The final steps in the analysis involved estimating the magnitude of informal economy and remittances of Mexico. The official estimate of the GNI of Mexico includes the formal economy, informal economy and the inflow of remittances in the economy (7). The estimated GDP of each state was summed to estimate GDP for all of Mexico. The GDP estimates of the states of Mexico derived from the DMSP OLS image by using the U.S. parameters can be said to also include the formal economy, informal economy and the estimates of the remittance inflow into Mexico (8). Inclusion of remittances within the GDP estimates seemed logical here (although remittances are usually included in the official estimates of GNI) because the residents of Mexico use the money sent to them as remittances to purchase material goods (including light bulbs) indicating improvement in the economy as measured from the nighttime lights. The official GNI of Mexico was then subtracted from the Estimated GDP of Mexico and this provided the predicted underestimation of informal economy and remittances in the official estimates (9).

Official estimates of GNI of Mexico = Formal economy + Informal economy + Remittances (7)

Estimated GDP of Mexico (using U.S. parameters) = Formal economy + Informal economy + Remittances (8)

Estimated GDP of Mexico – Official estimates of GNI of Mexico = Predicted underestimation of informal economy and remittances in the official estimates (9)

III. RESULTS

A. Actual and Estimated GDP of the U.S.

The log linear relationship between the area and population of the populated urban clusters of the U.S. provided estimates of the urban populations of all the states of the U.S. A simple multiple regression model was 'trained' using actual GDP for the U.S. states. The residual percentage of the actual and estimated GDP was calculated (10) and mapped in Fig. 4 to get a clear picture of the of the degree to which the estimated GDP was over or underestimated by the calibration multiple regression model.

((Actual GDP – Estimated GDP / Actual GDP) * 100) (10)

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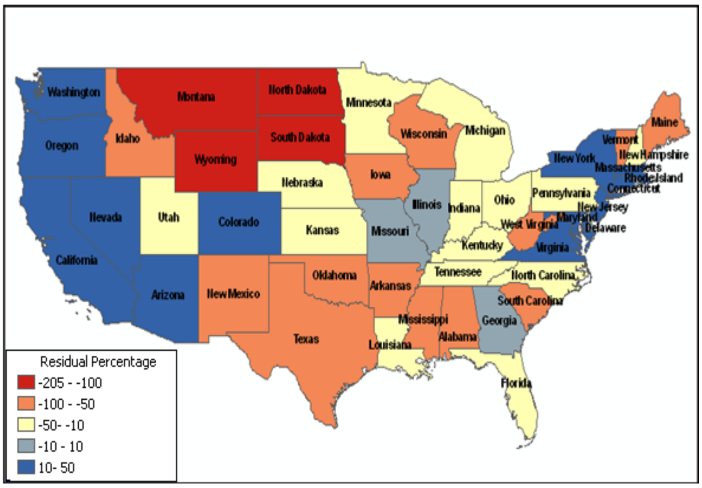

Figure 4. Percentage Residual GDP Map of the States of the U.S.

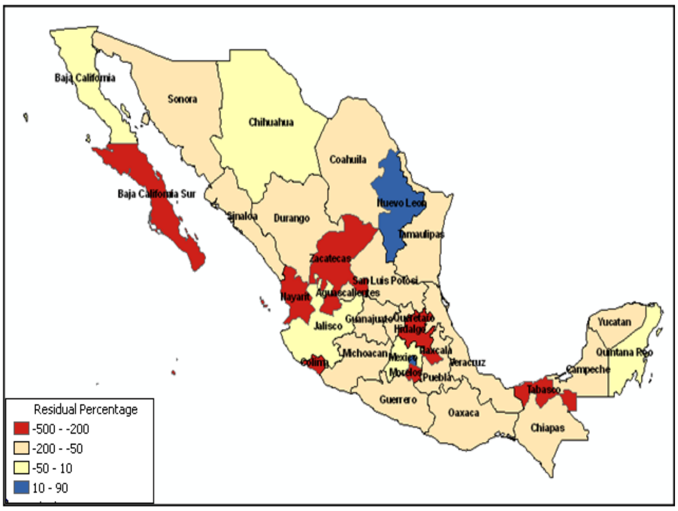

Figure 5. Percentage Residual GDP Map of the States of Mexico.

GDP was overestimated (greater than 100 percent) for the states of Montana, North Dakota, South Dakota, and Wyoming. These are also the states with the lowest official estimates of GDP. Texas, New York and California are the outliers, with GDP being overestimated for Texas and underestimated for California and New York in comparison to the official estimates (Fig. 2). These are also the three states with the highest official estimates of GDP – California, New York and Texas, in that order. The GDP of Texas may have been overestimated because of the prevalence of gas flaring which can be confounded with the nighttime lights on the DMSP OLS images. The underestimation in California and New York may be due to their coastal location and its impact on urban sprawl. It has been suggested by Sutton (2003) [50] that higher costs of coastal lands and the pressure to utilize coastal land intensively have probably restricted urban sprawl. This might account for lower urban sprawl in the states of California and New York and thus resulting in lower estimates of their GDP from the nighttime image.

B. Actual and Estimated GDP of Mexico

The calibration model developed to estimate the GDP of the states of Mexico using U.S. parameters resulted in an overestimation of GDP for all the states except for Distrito Federal and Nuevo Leon. Underestimation of GDP was the greatest for Distrito Federal (86 percent). The percentage residual map of Mexico is shown in Fig. 5.

In the 1:1 plot (Fig. 3) on which the Estimated GDP was plotted against the official GDP estimates of Mexico - Mexico State and Distrito Federal were the outliers. GDP was overestimated for Mexico State and underestimated for Distrito Federal. Distrito Federal was not included in the 1:1 plot because being the economic hub of the country it has an outlier effect and distorts the regression parameters of the model.

C. Estimating the magnitude of underestimation of informal Economy and remittances in the official measures of GNI, Informal Economy and Remittance of Mexico

The GDP of Mexico estimated from the nighttime image and on the basis of U.S. regression calibration model parameters was about 1041 billion dollars. It is assumed to include the formal economy, informal economy and remittances. The official estimate of GNI of Mexico is about 886 billion dollars [11]. Subtracting the official GNI of Mexico from the estimated GDP we derived the predicted underestimation of informal economy and remittances in the official estimates. In order to derive the magnitude of underestimation we first summed the official estimates of informal economy and remittances for the year 2000. Then we divided the predicted value of informal economy and remittances by the sum of the official estimates of informal economy and remittances. The result was that the official statistics underestimate informal economy and remittances by a factor of 1.5. In other words, the informal economy and the inflow of remittances may be about 1.5 times larger than what is recorded in the official estimates (Table 3).

TABLE III. DETERMINING THE MAGNITUDE OF UNDERESTIMATION OF INFORMAL ECONOMY AND REMITTANCES IN THE OFFICIAL ESTIMATES OF GNI OF MEXICO

	In Dollars
Estimated GDP of Mexico (formal+informal+remittances)	1,041 billion
Official estimates of the GNI of Mexico (formal+informal+remittances)	886 billion
Predicted underestimation of remittances and informal economy	155 billion
Official estimates of Informal economy in 2000	99 billion
Official estimates of remittances in 2000	7 billion
Total official estimates of informal economy and remittances	106 billion
Predicted underestimation of remittances and informal economy	155 billion
Total official estimates of informal economy and remittances	106 billion
Magnitude of underestimation	~ 1.5 times

IV. DISCUSSION

The radiance calibrated nighttime image of 2000-2001 and the adjusted official measures of GDP of the U.S. were used to develop a calibration regression model for estimating the GDP and GNI for Mexico. We found that most states in Mexico have a surplus in lighting compared to their officially reported GDP. This surplus in lighting can be attributed to the informal economy and inflow of remittances in Mexico. Although some of the disaggregated GDP values of the states of Mexico have large residual errors the power of the mean strengthens our argument that the informal/remittance economy of Mexico is larger than the official estimates.

This method is clearly still in the 'exploratory' stage. Our initial results suggest that further research using other countries, finer resolution imagery, and more accurate spatially disaggregate economic numbers will demonstrate the validity of this approach.

V. CONCLUSION

This research focuses on developing a model for estimating the location and magnitude of GDP, informal economy and remittances for the upper middle income country of Mexico. The model is 'trained' by using the published GDP estimates of the U.S. The model is based on the assumptions that economic activity creates the same spatial patterns of nighttime lights in Mexico and the United States; spatial patterns of GDP per capita and distribution of wealth are uniform in both the U.S. and Mexico; and, estimated urban populations are used as a proxy measure of economic activity because spatially disaggregate GDP data are either not available or do not exist. The results obtained suggest that the informal economy and inflow of remittances in Mexico may be approximately 1.5 times larger than the published official estimates.

The informal economy is expanding in Mexico after the economic restructuring following NAFTA. The difficulties associated with collecting informal economic data and the lack of international standards to compare data on informal economy further hinders the proper estimation of informal economy. We provide a simple and independent method for estimating and mapping economic activity. The increased spatial, spectral and radiometric resolution of future and potential nighttime satellite missions (Visible Infrared Imaging Radiometer Suite and Nightsat) [51] may dramatically improve these methods.

Taking into consideration the continuous growth of population, the ever changing economy in the era of globalization, the instability associated with informal economy and unrecorded remittances, we can anticipate that the quality and availability of the official estimates of informal economy and remittances will continue to deteriorate. Therefore, models derived from nighttime imagery may prove useful for estimating population distribution and associated socio-economic variables for decades to come. This may help economists and policy makers understand the economic situations of countries, detect the shortcomings in economic structures, improve employment opportunities, reduce poverty and undertake other constructive economic development policies.

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